www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

Wireless sensing of open loop micro inductors using Helmholtz coil

A.Yousaf, F.A.Khan and Prof. Dr. L.M Reindl

Laboratory for Electrical Instrumentation

Department of Microsystems Engineering IMTEK

University of Freiburg, Germany

Emails: adnan.yousaf@imtek.uni-freiburg.de

Submitted: Nov. 11, 2011 ***Accepted: Nov. 23, 2011*** ***Published: Dec. 1, 2011***

Abstract- This paper reports wireless sensing of open loop micro inductors parameters i.e. distributed capacitance, inductance, resistance and Q factor in presence uniform magnetic fields generated by Helmholtz coils pair. A frequency dependent analytical model is developed which models the inductively coupled system including the effects generated by the presence of test micro coil in uniform magnetic field. Micro inductor parameters are extracted from the remotely measured impedance signal and compared with the developed modeled. Further to visualize the magnetic field coupling effects and numerically compute the micro inductor parameters, FEM simulation is performed using HFSS and COMSOL Multiphyscics.

Index terms***: Magnetic coupling, Helmholtz coils, micro inductors, HFSS.***

1. INTRODUCTION

Among the passive components micro coils or inductors are one of the most fundamental part used in RF circuit design. Rapid developments in micro systems technology drastically reduced the size of electronics components (passive and active).This miniaturization in size made it difficult to test and characterize the micro coils parameters precisely before they are being implemented. Conventional micro coil test systems are based on wired mechanical ohmic contacts as shown in figure 1 which not only damage the micro coil structure but also make the proper contacting process tedious.

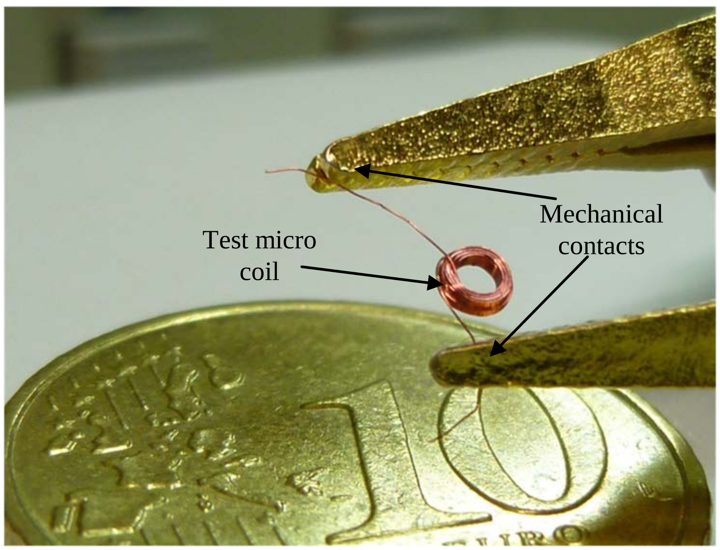


Figure 1: Mechanical contact based micro coil measurement

Further these contacts introduce contacting lead effects which get difficult to remove from the actual micro coil parameters i.e. Inductance, distributed capacitance and resistance. This requires investigation of new wireless measurement test systems which can be integrated in micro coil production and test units. In this work we develop a new technique to measure and analyze the behavior of open ended test micro coils by using a pair of accurately designed Helmholtz coils.

To date the investigations done on the micro coils and RLC passive sensors were based on the wireless measurement of resonance frequency or Q factor as in [1] where the developed method is based on simultaneous application of three excitation signals of constant amplitude with different frequencies. Wirelessly measuring un-terminated or open ended micro coils is presented in [2] where a test micro coil is inductively coupled to an electrically small magnetic loop antenna with constant current distributions around the loop antenna. The idea of inductively coupled wireless capacitive sensor where the applied pressure, humidity, temperature and strain changes are measured using an LC circuit, are presented in [3, 4, 5, 6, 7, 8]. Investigation of temperature and magnetic field dependent radiofrequency electromagnetic absorption in polycrystalline by monitoring changes in resonance frequency and current of LC resonant circuit is reported in [9].Wireless read out of passive LC sensors is presented in [10] where the read out is performed using an analog front end circuit based on demodulation for mapping the real part of the reader coil impedance to a dc output voltage All of these publications focused on the concept based on passive inductive coupling and sensing the change in the capacitance of LC closed loop resonance circuit in presence of weak or non-uniform magnetic fields. Here we present a novel method to measure, test and analyze the open ended test micro coil in uniform magnetic field generated at the center of precisely designed Helmholtz coil pair. This paper is organized as follows. In section 2 we discuss the theoretical background of inductively coupled systems and Helmholtz coil. Section 3 focuses on the wireless measurement system. Results from measurement and simulations are presented in section 4. Conclusion and outlook are discussed in section 5.

2. Theoretical background

2.1 Inductively coupled systems

Inductive or magnetic coupling is one of the most frequently used and easily implementable techniques in direct sensing of non electrical information like humidity, pressure, temperature etc. The magnetic coupled system in general composed of two subsystems. The primary system is the reader or the excitation unit which is an AC transceiver creating an electromagnetic field in the surrounding region. Secondary unit is the sensing unit which is placed in the magnetic field generated by the reader unit. Figure 3 depicts the phenomena of the inductive coupled systems.
The sensing unit in inductively coupled passive sensor systems is embedded in an LC tank or a sensing coil. The inductance L_s and capacitance C_s of the sensing coil forms a resonant circuit.
Sensing element detects the stimulus signal and in effect changes the resonant frequency of the sensing unit

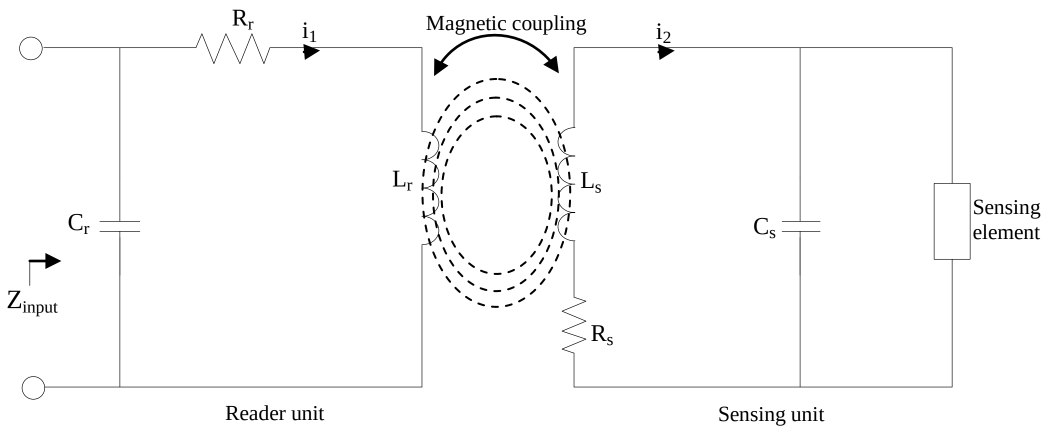


Figure 2: Direct wireless passive sensing using inductive link.

Improved flux linkage can be obtained by bringing the sensing unit in the near field electromagnetic area defined by the following equation 1.

$$D = \frac{\lambda}{2\pi} \tag{1}$$

Where λ is the wavelength of the applied AC signal. In near field improved flux increases the induced current i_2 hence absorbing more energy from the reader unit. This absorbed energy or the induce current is reflected back to the input impedance Z_{input} through the reflected impedance Z_{ref} as shown in the equivalent schematics in figure 3.

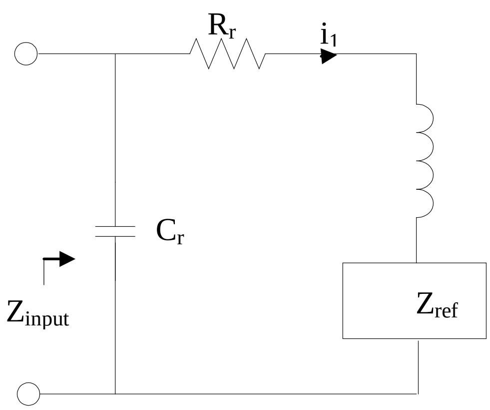


Figure 3: Equivalent schematic of the inductively coupled system.

Analyzing the change in the resonance frequency of the reflected impedance Z_{ref} the variations in the detecting sensing unit are investigated.

2.2. Theory of Helmholtz coil

Since decades Helmholtz coils are famous for generation of uniform magnetic field regions and used in many applications like sensor probes for EMI sensing or displacement sensing etc. Helmholtz coil pair consists of two circular set of coils of equal diameter and number of turns parallel along the axis joining the pair. Helmholtz coils can be configured (based on the application) in series or parallel aiding connection. The Helmholtz coil pair is separated by a distance equal to the diameter of the coils used. From the basic understanding of electromagnetic and Maxwell's equations we know that alternating electric field generates an alternating magnetic field and vice versa. In case of Helmholtz coil when the magnetic field is deliberately created between the pair of coils, it creates a series of electric and magnetic field in the test region where the uniform magnetic region is desired. Helmholtz coil pair may consist of single turn on each side or same multi-turns on each side. In case of constructing multi-turns Helmholtz coils the windings in both the pair should be same and the windings diameter in each coil must be less than the coil diameter, further the applied AC signal or the electrical current direction in both the coil pair should be same i.e. either clockwise or counter clockwise. Figure 4 shows a typical arrangement of a Helmholtz coil pair.

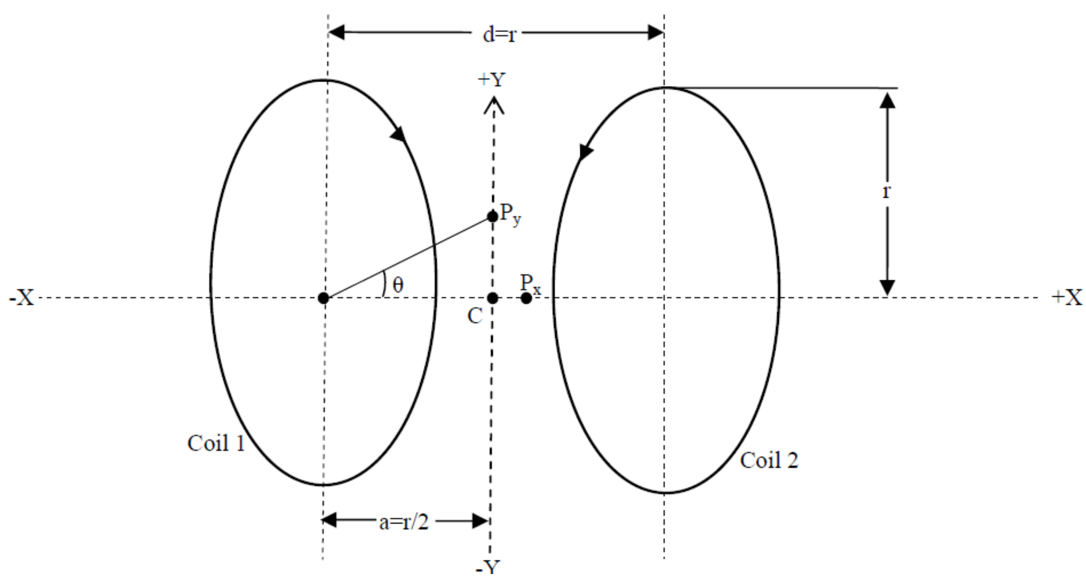


Figure 4: Helmholtz coil pair arrangement

The driving current through the Helmholtz coil pair generates a uniform magnetic field between the centers of the coil pairs. The magnetic field uniformity depends upon the accuracy with which the Helmholtz coil pair is constructed and the precision by which the current is maintained through the coil pair. Axial magnetic field strength H_x in A/m can be calculated at any point P_x on the common axis joining the two coils using equation 2 as given in [11, 12].

$$H_x = \frac{N_1 I r_1^2}{2(\sqrt[3]{r_1^2 + a_1^2})} + \frac{N_2 I r_2^2}{2(\sqrt[3]{r_2^2 + a_2^2})} \tag{2}$$

Where N and r are the number of turns and the separation distance between the coil pair. x and I are the axial position of the magnetic field (in meters), current flowing through the coils. At the center position C (i.e. x=0) the equation 2 can be simplified when both the coil pair have equal number of turns, coil diameter and radius (as given in equation 3 for calculating the magnetic field at H_c

$$H_c = \frac{NI}{r(\sqrt[3]{1.25})} \approx \frac{0.7155NI}{r} \tag{3}$$

3. Wireless Measurement System

The wireless measurement system overview is shown in figure 5.

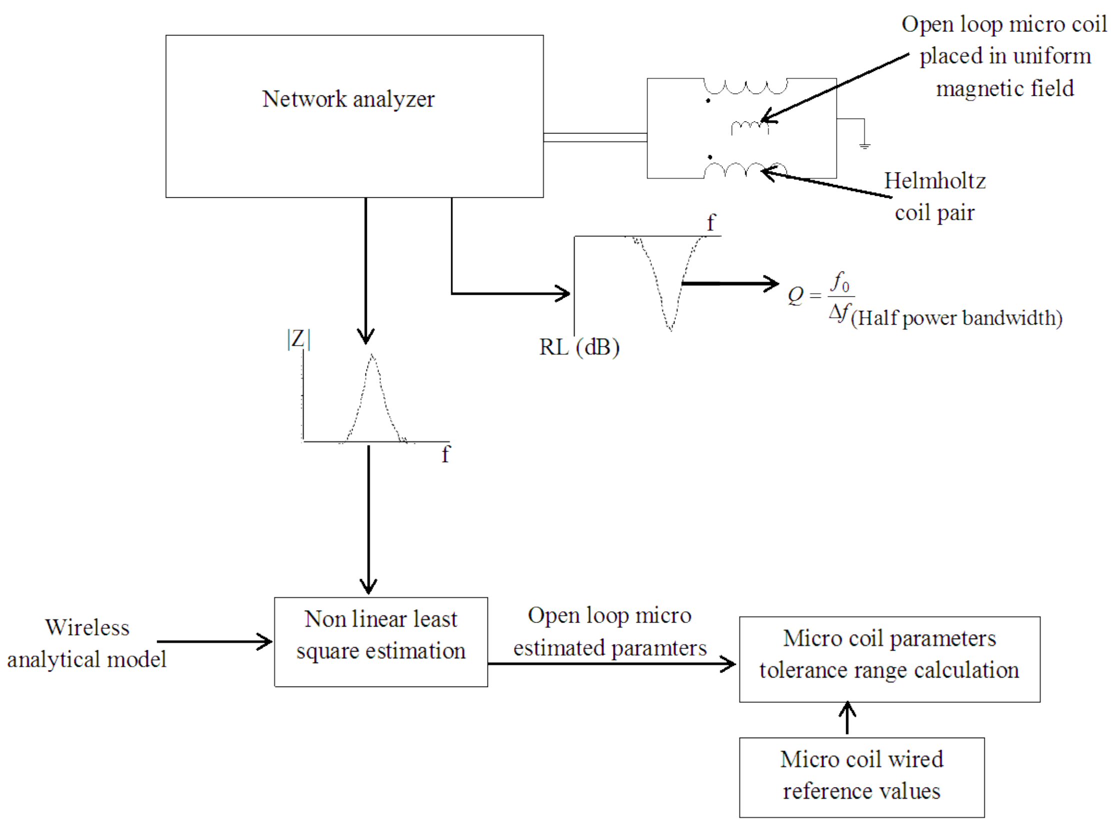


Figure 5: Wireless measurement system overview.

The open loop test micro coil is wirelessly measured using the network analyzer in uniform magnetic field generated by Helmholtz coil pair as shown in 5. Impedance magnitude (both real and imaginary) and return loss signal are wirelessly measured. From the return loss signal the quality factor is calculated using the half power bandwidth approach. The impedance magnitude and the wireless analytical model (modeling all the unknown parameters) are applied to the developed non linear least square estimation. Wired reference parameters of the micro coil and the wirelessly estimated parameters are then used to calculate the tolerance range between the wired and wireless readings.

3.1. Wireless Analytical Model

Equivalent lumped electrical parameter wireless model of the system is shown in figure 6.

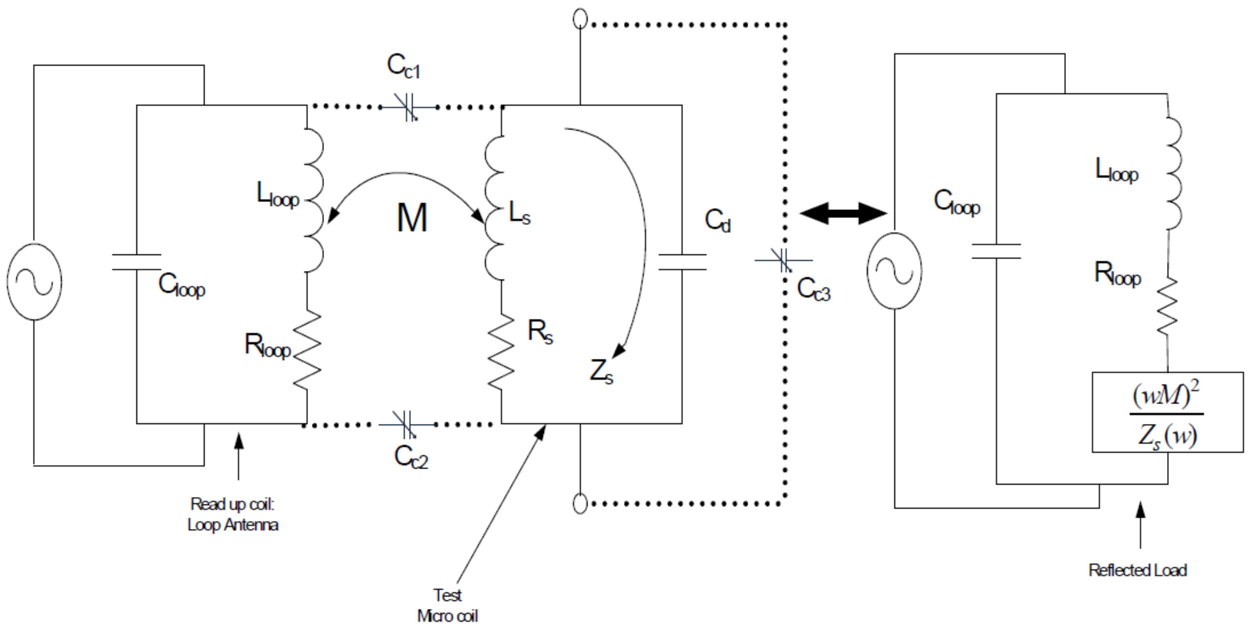


Figure 6: Equivalent circuit model of wirelessly inductive coupled system.

As shown in figure 6 Open loop micro coil parameters i.e. inductance, inter-winding capacitance and resistance are given by L_2, C_2 and R_2 with C_{c1} and C_{c2} are the frequency dependent coupling capacitors modeling the capacitive coupling effects between the Helmholtz coil pair and the test micro coil. The analytical model of the coupled system is given in equation 4 which is derived using standard transformer equations.

$$Z_{wireless} = \frac{R_1 + jwL_1}{1-(C_g + C_p + C_1)\left\{ jwR_1 + w^2 L_1 \right\}} + \frac{(wM)^2}{\dfrac{jwL_2 + R_2}{1 - w^2 L_2 C_2 + jwR_2 L_2} + \dfrac{1}{jwC_{c1}} + \dfrac{1}{jwC_{c2}}} \tag{4}$$

With L_1, C1 and R_1 are the total inductance, resistance and capacitance of the Helmholtz coil pair. Cp and Cg models the parallel (capacitance between the turns) and the ground capacitance. Where w is the angular frequency and M is the mutual inductance and defined in equation 5.

$$M = K\sqrt{L2 * L1} \tag{5}$$

K is the coupling coefficient and is a function of distance or placement of test micro coil in the uniform magnetic field region generated by Helmholtz coil. Since the movement of the open ended test micro coil is limited the position dependent coupling coefficient K is limited between 0 to 0.10.

3.2. Design of Helmholtz Coil.

Helmholtz coil is designed using one coil per pair separated by distance r equal to the radius of the coil as shown in figure 7.

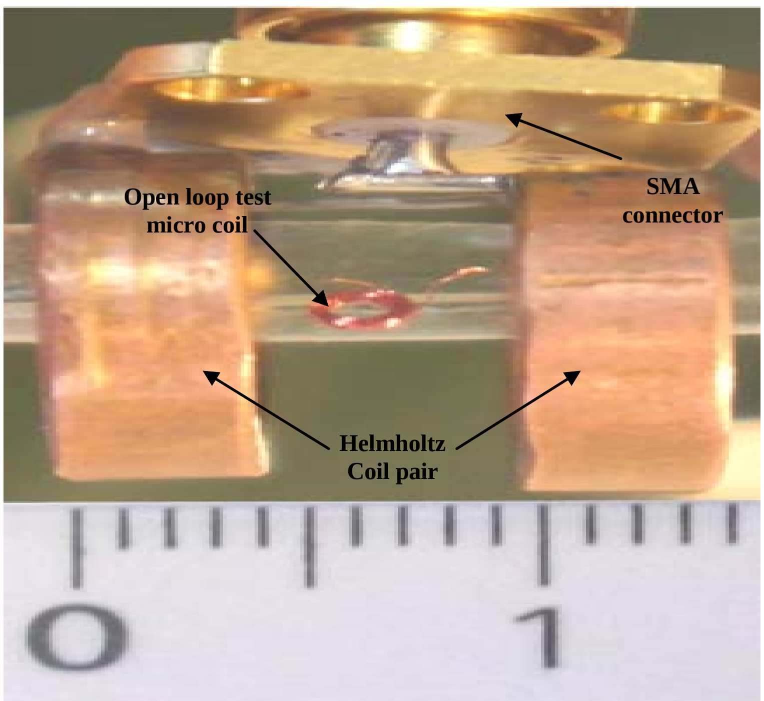


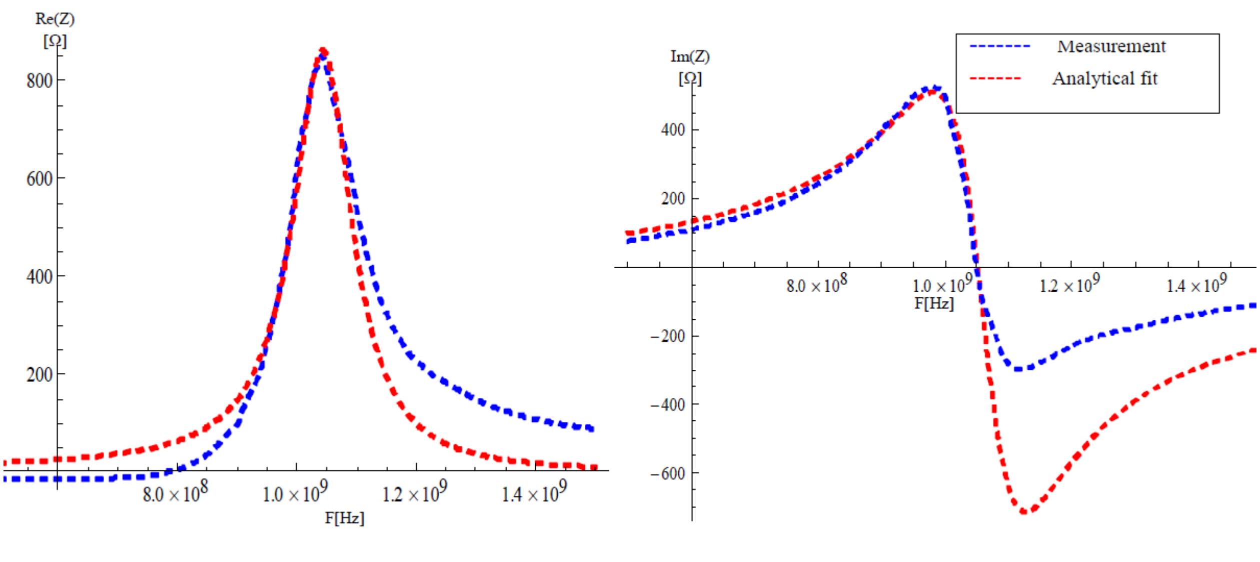
Figure 7: Designed Helmholtz coil magnetically coupled to an open loop test micro coil.

The specifications of the designed Helmholtz coil are given in table 1.

Table 1Design Specifications of the Helmholtz coil

N	r[cm]	D_h [cm]	W_h [cm]
1	0.75	1.5	0.4

Where N is turns equal on each side, r is the average radius or the separation between the series aided coils D_h is the diameter of the coils and W_h is the coil wire radius. In order to characterize the Helmholtz coil behavior at high frequencies, the Helmholtz coil is measured without the presence of device under test i.e. test open loop micro coil. Figure 8a and b shows the real and imaginary part of measured impedance and analytical fit.



(a) (b)

Figure 8: Helmholtz coil measured impedance (real 8a and imaginary part 8b) and analytical fit

Table 2 contains the Helmholtz coil measured parameters.

Table 2: Helmholtz coil measured parameters.

L_1 [µH]	C_1 [pF]	C_p [pF]	C_g [pF]	F_r [GHz]
0.025	0.22	0.60	0.75	1.04

Where F_r is the self resonance frequency of the Helmholtz coil.

3.2.1 Radial Magnetic field

The radial magnetic field strength and uniformity of the designed Helmholtz coil at different positions of the coil axis can be calculated using approximations given in [13, 14] Equation 6 gives the radial magnetic field strength Hρ at a point (e.g P_y as shown in figure 4) off the coil axis.

$$H_\rho = h_{\rho 1} + h_{\rho 2} \tag{6}$$

$h_{\rho 1}$ and $h_{\rho 2}$ are the magnetic field contributions from coil 1 and 2 respectively which are calculated as given in equation 7 and 8.

$$h_{\rho 1} = \frac{NI}{2\pi} \frac{1}{\sqrt{(1+\frac{y}{r})^2 + k_1^2}} \left[f_1(\theta) + g_1(\theta) \frac{1-(\frac{y}{r})^2 - k_1}{(\frac{y}{r})^2 + k_1^2} \right] \tag{7}$$

$$h_{\rho 2} = \frac{NI}{2\pi} \frac{1}{\sqrt{(1+\frac{y}{r})^2 + k_2^2}} \left[f_2(\theta) + g_2(\theta) \frac{1-(\frac{y}{r})^2 - k_1}{(\frac{y}{r})^2 + k_2^2} \right] \tag{8}$$

Where f_c (θ) and g_c (θ) are defined by following equations.

$$f_c(\theta) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1-\rho_c^2 \sin^2 \theta}} \tag{9}$$

$$g_c(\theta) = \int_0^{\frac{\pi}{2}} \sqrt{1-\rho_c^2 \sin^2 \theta} d\theta \tag{10}$$

With ρ_c and k_c defined as with c used as a subscript for coil pair 1 or 2.

$$\rho_c = \sqrt{\frac{4(\frac{y}{r})}{(1+\frac{y}{r})^2 + k_c^2}} \tag{11}$$

$$k_1 = \frac{x}{r} + \frac{1}{2} \tag{12}$$

$$k_2 = \frac{1}{2} - \frac{x}{r} \tag{13}$$

Figure 9 shows normalized magnetic field strength relative to center Hρ/Hc versus the axial distance from the center x/r plotted for several values of the radial distance from the center y/r.

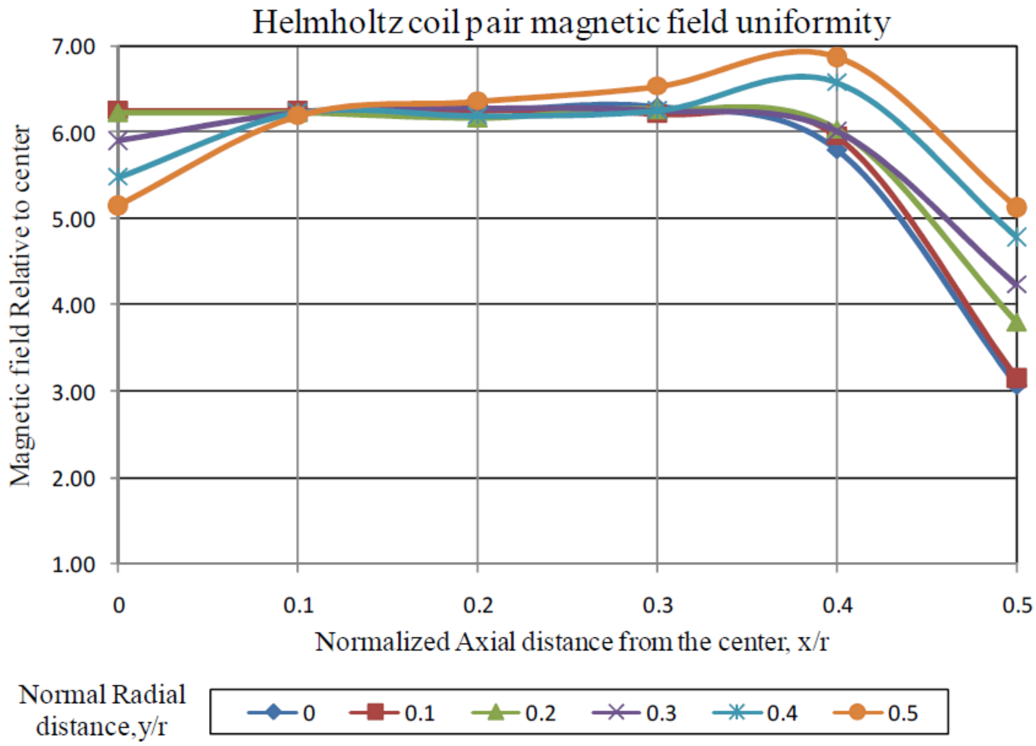


Figure 9: Normalized magnetic field strength.

3.2.2. Helmholtz coil and device under test (DUT) size limitations

Based on the dimensions of DUT, it is possible to determine the size requirement of Helmholtz coil pair (as given in [14]) for generating maximum uniform magnetic fields with uncertainties. Table 3 shows the magnetic field uncertainties for different values of normalized radii of the designed Helmholtz coil.

Table 3: Magnetic field uniformity of the designed Helmholtz coil for different values of normalized radii.

Field uncertainties	1%	3%	7%	10%
± x/r	0.2	0.3	0.4	0.5
± y/r	0.2	0.3	0.4	0.5

Equation 14 describes the method to calculate the maximum radii (r) of Helmholtz coil needed to test a DUT of given dimensions.

$$r = \frac{\text{DUT Dimension}(cm)}{2 \times \text{Field uncertainties}} \tag{14}$$

With the specifications of the designed Helmholtz coils (as given in table 1) it is possible to measure the test open loop micro coils (DUT) with a maximum coil diameter of 0.45cm in uniform magnetic field with an uncertainty of 1%.

4. Results

4.1 Measurement results

Test open ended micro coils are wirelessly measured by placing them in region of uniform magnetic field generated by Helmholtz coil pair as shown in 7.Tested micro coils have the self resonating frequencies between 1 to 100Mhz.Thewirelessly measured impedance signal (both real and imaginary parts) and the wireless analytical model (as given in equation 4) are applied to the non linear least square estimation routine developed in mathematica. Further the parameter of interest i.e. test micro coil inductance, capacitance and resistance including the unknown parameters are extracted from the developed estimation routine. The best estimated extracted parameters are fitted back to the developed analytical model. Figure 10 shows the analytical fit and the wireless measurement of real and imaginary impedance of test micro coil with 33 turns and a self resonance frequency of 51 MHz.

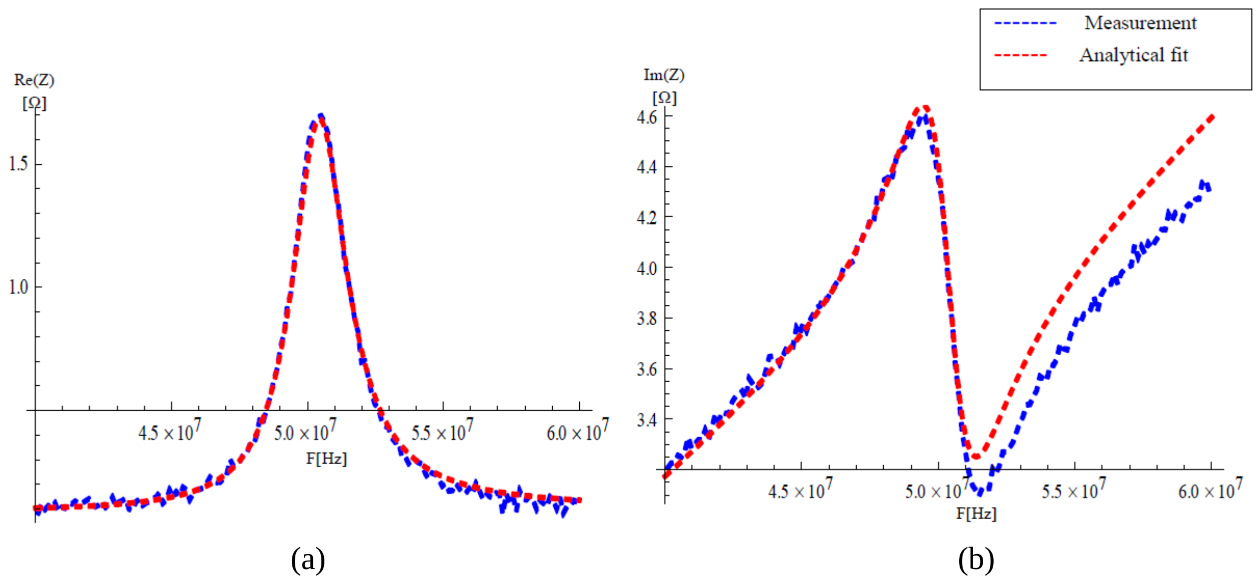


Figure 10: Wirelessly measured impedance (real 10a and imaginary part 10b) and analytical fit.

Similarly loaded Q factor is calculated by measuring the return loss signal and using the half power bandwidth formula (as described in [15]) as given in 15

$$Q_L = \frac{f_0}{\Delta f} \tag{15}$$

Where f_0 is the wirelessly measured resonance frequency and Δf is the frequency difference between the upper and lower half power bandwidth frequency points from the measured return loss signal. Table 4 and 5 contains the wired and wireless measurement of tested micro coils.

Table 4: Wired measurement of micro coils.

N turns	L_{wired} [μH]	C_{wired} [pF]	R_{wired} [Ω]	Q_{wired} factor	f_{wired} [MHz]
33	10.1	0.968	270	11.95	50.93
60	16.8	1.27	248	14.63	34.47
100	14.04	0.961	340	11.23	43.35
200	164	3.73	906	7.32	6.43
300	248	1.60	1238	10	7.99
500	738	3.18	1680	9.07	3.26

Table 5: Wirelessly extracted open loop micro coils parameters in uniform magnetic field:

N turns	L_2 [μH]	C_2 [pF]	R_2 [Ω]	Q_L factor
33	9.62	0.995	252	11.21
60	16.1	1.21	232	13.8
100	13.40	0.922	311	10.63
200	160.4	3.65	862	6.97
300	242.2	1.56	1169	9.63
500	718.3	3.15	1538	8.78

The wireless resonance frequency of the open ended test micro coils is calculated by using the following equation 16.

$$f_{wc} = \frac{1}{2\pi\sqrt{L_2 \Delta C}} \tag{16}$$

Where ΔC is given in equation 17 which is the test micro coil capacitance C_2 influenced by the series combination of frequency depended coupling capacitances.

$$\Delta C = C_2 + (C_{c1} \parallel C_{c2}) \tag{17}$$

Table 6 contains the wirelessly measured (f_{wm}) and calculated resonance frequency (f_{wc}) using equation 16 and 17.

Table 6: Wirelessly measured and calculated resonance frequencies.

N turns	f_{wm} [MHz]	f_{wc} [MHz]
33	51.3	51.46
60	34.56	34.72
100	43.94	44.03
200	6.48	6.53
300	7.95	8.01
500	3.38	3.42

Table 7 contains the percentage error compared with the wired measurement of the tested micro coils.

Table 7: Percentage error between the wirelessly extracted and wired parameters of the micro coils.

N turns	L%	C%	Q% factor	F %
33	4.72	2.71	6	1
60	4.16	4.7	5.67	0.72
100	4.55	4.90	5.34	1.54
200	2.19	2.11	4.78	1.53
300	2.33	2.5	3.7	0.24
500	2.66	0.94	3.26	1.72

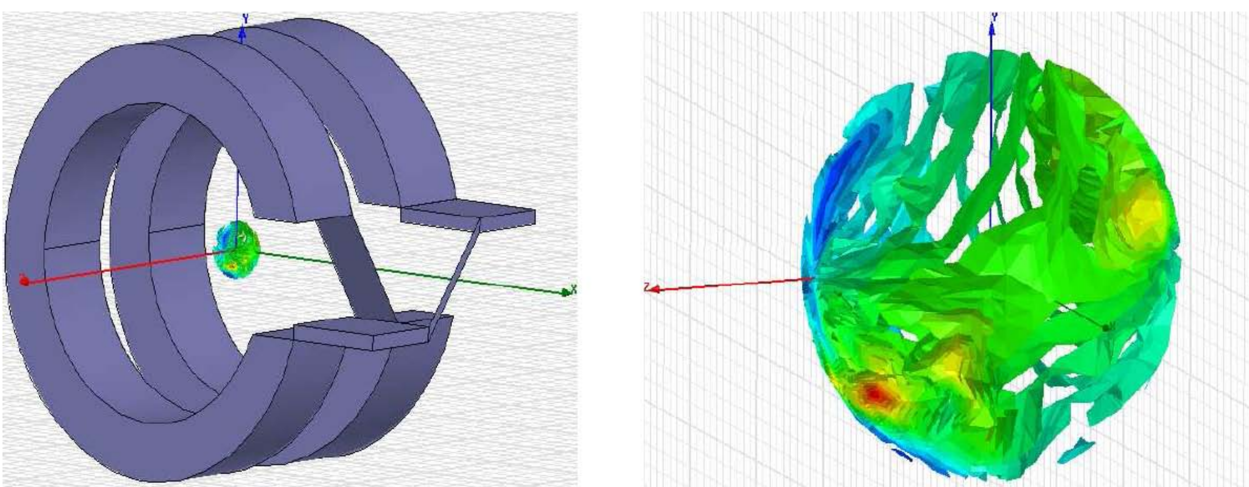
The wirelessly tested open loop micro coils which had the measured resonance frequencies f_{wm} less then 10MHz show less percentage error in the extracted parameters i.e. inductance, capacitance , Q factor and calculated wireless resonance frequency f_{wc}.

The reason behind the reduced errors is due to the maximum frequency of operation F_{op} limitations of the designed Helmholtz coil pair as given in [14].A practical F_{op} is achieved about 2 order of magnitude below the self resonance frequency of the Helmholtz coils. After this frequency the current of the Helmholtz coil pair falls and the magnetic field homogeneity is degraded. In the designed Helmholtz coil (with the specification given in table 1 and 2) the maximum frequency of operation is Fop is about 10MHz.Hence the micro coils having resonance frequency above 10MHz had more errors as compared to the other test micro coils having resonance frequencies below 10MHz.

4.2 Simulation results

4.2.1. Helmholtz Coil 3D simulation Model

High Frequency Structure Simulation (HFSS) is used to perform 3D electromagnetic simulation, hence assisting to study the uniform magnetic field behavior of the designed Helmholtz coil. Figure 11a shows the 3D simulation model of Helmholtz coil.



a) b)

Figure 11: 3D simulation model in 11a and magnetic field behavior in 11b.

In this simulation model a Helmholtz coil pair is modeled as shown in figure 7.Instead of a test micro coil a sphere region is created at the center of the Helmholtz coil pair. Magnetic field uniformity can be seen at the center of the Helmholtz coil pair(as shown in Figure 11b.) which changes consistently with better uniformity due to the symmetrical structure of the Helmholtz coil.

4.2.2. 2D FEM simulation of the magnetic coupled system

All the wirelessly tested micro coil were air core, multi turn and layer micro coils with insulated copper wire conductor coated with base coating of polyurethane and top coating of polyamide. Figure 12 shows the cross section microscopic view of a test micro coil with 33 turns.

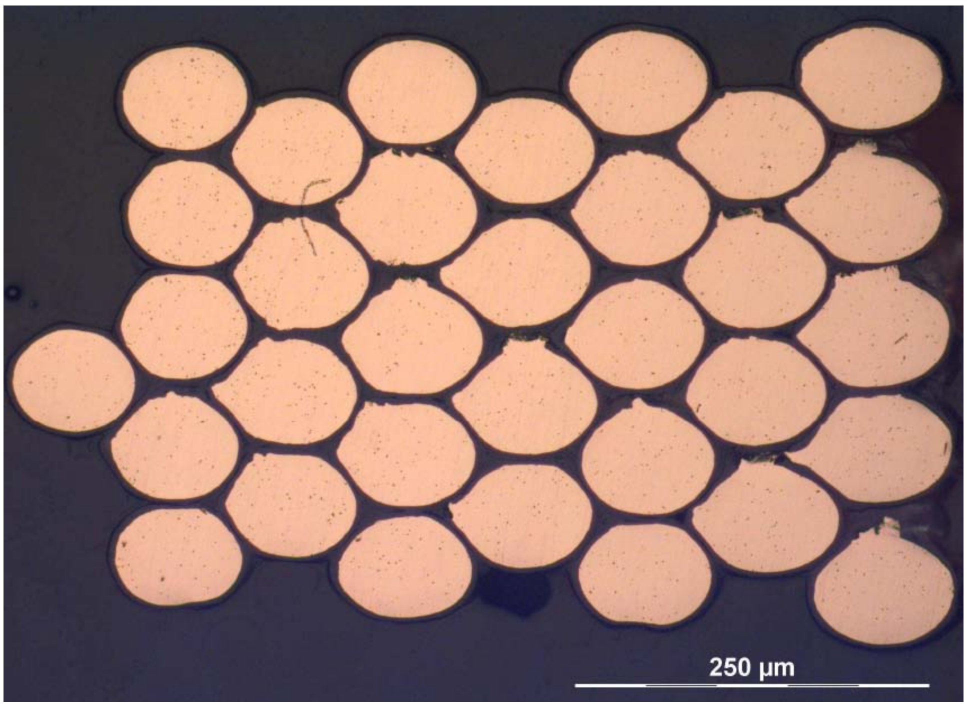


Figure 12: 33 turns micro coil cross section microscopic view.

Due to the micro coil structural complexities, a 2D geometry is constructed in order to calculate the micro coil parameters in uniform magnetic field. Magnetic coupled system is modeled in 2D axial symmetrical using ACDC module of COMSOL Multiphyscics. Test micro coil structure (as shown in figure 12) is constructed using a 2D cross section array of circular loops (each loop modeling a cross section of insulated wire). Similarly the Helmholtz coil pair is modeled in 2D by making two equally separated rectangular cross section of copper. As shown in Figure 13a where an equal frequency AC signal in same direction is applied to both the rectangular cross section without the presence of a test micro coil, hence agitation of the magnetic field is minimum. 2D array of wire loops is constructed modeling the test micro coil cross section placed at the center of the Helmholtz coil (as shown in 13b).

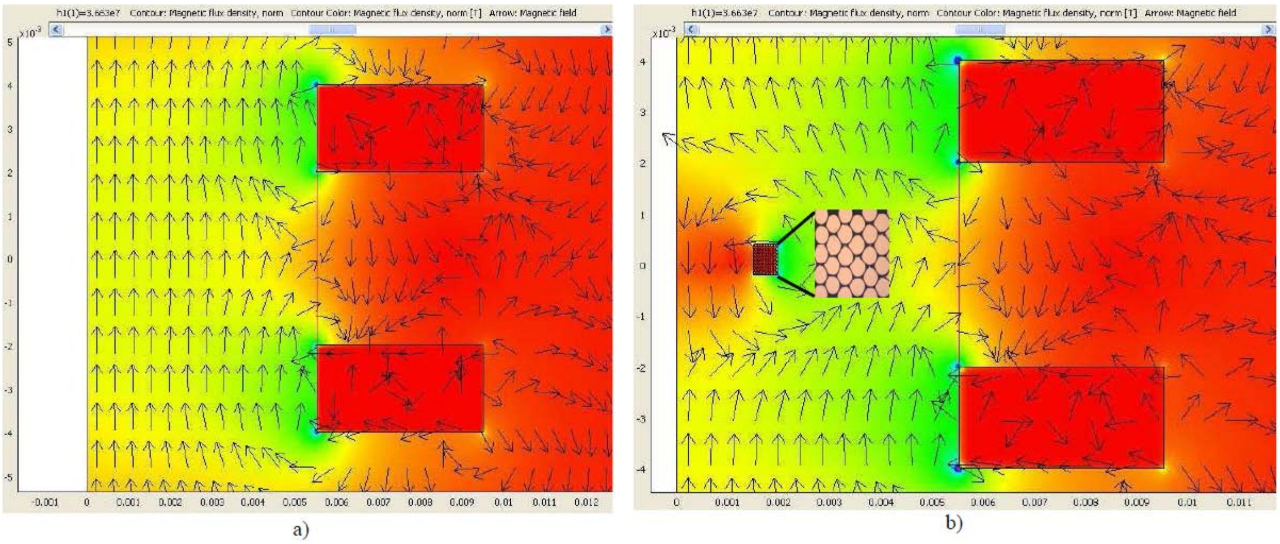


Figure 13: Magnetic field behavior and flux densities of the inductively coupled system without 13a and with a test micro coil 13b.

Since the tested micro coils are within the DUT limitations as discussed in section 2 the magnetic field is unchanged which can be seen in 13b where a test micro coil is placed in uniform magnetic region. The test micro coil parameters are numerically calculated by measuring the magnetic flux connecting the test micro coil Φ_{sim} at the constructed 2D coil array boundary and the total induced current I_{Total} through the Helmholtz coil pair rectangular cross sections is calculated by providing a frequency sweep. Using Φ_{sim} and I_{Total} , the test micro coil inductance L_{sim} is numerically calculated as given in equation 18.

$$L_{sim} = \frac{\Phi_{sim}}{I_{Total}} \times n^2 \tag{18}$$

Where n is the number of turns of the test micro coil. The effect of distributed frequency dependent capacitance is numerically calculated as given in 19.

$$C_{sim} = \frac{1}{w^2 \times L_{sim}} \tag{19}$$

Table 8 contains the inductances L_{sim}, distributed capacitance C_{sim} and the resonance frequency numerically calculated using COMSOL.

Table 8: Numerically calculated micro coil parameters in COMSOL

N turns	L_{sim} [µH]	C_{sim} [pH]	f_{sim} [MHz]
33	9.48	1.004	51.6
60	15.8	1.31	34.92
100	13.28	0.997	43.74
200	156.4	3.54	6.72
300	234	1.968	7.42
500	712	3.37	3.25

5. Conclusion and Outlook

In this paper open loop micro coil parameters i.e. inductance, inter winding capacitance ,resistance and Q factor are wirelessly measured in uniform magnetic field generated by precisely designed equally spaced Helmholtz coil pair. Normalized magnetic field strength is calculated for the designed Helmholtz coil pair at different radial and axial points. Open loop test micro coil is placed at the center of the Helmholtz coil pair. A wireless analytical model is developed for the inductively coupled systems which includes frequency dependent coupling capacitances in uniform magnetic fields. It is found here that with the test micro coils having self resonance frequencies within the operational limiting frequency, it is possible to measure micro coil parameters to less than 2%.3D simulation model for the designed Helmholtz coil is used to visualize the magnetic field uniformity in the region where the DUT is placed i.e. center of the Helmholtz coil pair. Due to structural complexities of multilayer test micro coil, the magnetic coupled system is modeled in 2D using COMSOL Multiphyscics and simulated. The simulation results for the Inductance and capacitance are presented which are close to the extracted results from wirelessly measured signal. Future work will focus on error optimization of the wirelessly measured micro coil parameters using adaptive least Square estimation approach.

6. Acknowledgment

The authors would like to thanks German Federation of Industrial Research Associations AIF, the company Hopt GmbH for supporting this project and Dipl.-Ing. Thomas Ostertag for his technical support.

REFERENCES

[1] S. Pichorim, P. Abatti, A novel method to read remotely resonant passive sensors in bio telemetric systems, Sensors Journal, IEEE 8 (2008) 6 –11.

[2] A.Yousaf,T Jeager, L. Reindl, 2011. Wireless Measurement System for Extracting Open Loop Micro Coil Parameters,FREQUENZ, Journal of RF/Microwave Engineering, Photonics and Communications, Special Issue GeMiC2011.

[3] M. Nowak, N. Delorme, E. Colinet, G. Jacquemod, F. Conseil, A readout circuit for remote interrogation of capacitance transducers, Integration Issues of Miniaturized Systems - MOMS, MOEMS, ICS and Electronic Components (SSI), 2008 2nd European Conference Exhibition on (2008) 1 –8.

[4] M. Fonseca, J. English, M. von Arx, M. Allen, Wireless micro machined ceramic pressure sensor for high-temperature applications, Micro electromechanical Systems, Journal of 11 (2002) 337 – 343.

[5] A. Baldi, W. Choi, B. Ziaie, A self-resonant frequency-modulated micro machined passive pressure transensor, Sensors Journal, IEEE 3 (2003) 728 – 733.

[6] M. Silva, F. Vasconcelos, Temperature sensing system with short-range wireless sensor based on inductive coupling, Sensors Journal, IEEE 11 (2011) 2469 –2478.

[7] M. Nowak, E. Colinet, N. Delorme, F. Conseil, G. Jacquemod, A wireless sensing platform for battery-free sensors, in: Circuits and Systems,2008. ISCAS 2008. IEEE International Symposium on, pp. 2122 –2125.

[8] K. Fotopoulou, B. Flynn, Wireless powering of implanted sensors using rf inductive coupling, in: Sensors, 2006. 5th IEEE Conference on,pp. 765 –768.

[9] V. B. Naik, R. Mahendiran, Magnetically tunable rf wave absorption in polycrystalline, Applied Physics Letters 94 (2009).

[10] R. Nopper, R. Has, L. Reindl, A wireless sensor readout system 02014;circuit concept, simulation, and accuracy, Instrumentation and Measurement, IEEE Transactions on PP (2011) 1 –8.

[11] Y. J. Song Qiyhu, Wang Wenijian, 2010. Study on Uniform Magnetic field in Helmholtz Coils by Simulation, Safety and EMC.

[12] E. Bronaugh, Helmholtz coils for emi immunity testing: stretching the uniform field area, in: Electromagnetic Compatibility, 1990. Seventh International Conference on, pp. 169 –172.

[13] L.B.leob, Fundaments of Electricity and Magnetism, Dover Publications Inc.NY, 3rd edition, pp. 56–62.

[14] E. Bronaugh, Helmholtz coils for calibration of probes and sensors: limits of magnetic field accuracy and uniformity, in: Electromagnetic Compatibility, 1995.Symposium Record. 1995 IEEE International Symposium on, pp. 72 –76.

[15] D. C. Dube, 1997. Dielectric Measurements on High-Q Ceramics in the Microwave Region,Journal of the American Ceramic Society.